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# EPDM Rubber Reclaim from Devulcanized EPDM

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**ABSTRACT:** Two types of ethylene–propylene–diene monomer (EPDM) rubbers, namely an efficient vulcanized (EV) and a semiefficient vulcanized (SEV), have been used to produce devulcanizates in a continuous setup. The devulcanizates are re-cured using the same recipes as for the virgin rubber. The influence of mixing it with virgin rubber compound, the addition of extra sulfur, the operating devulcanization conditions, and the excess of devulcanizing agent on the mechanical properties (hardness, tensile strength, and compression set) of the reclaim rubbers are studied. Most of the reclaims produced show slightly inferior mechanical

properties compared to the virgin rubber. Surface imperfection was observed on the devulcanizate with high devulcanizing agent content. Excellent mechanical properties (all above the standards) of the reclaim were found when the devulcanized profile material was used (EV-EPDM) to replace the virgin one for application as a roofing sheet material (SEV-EPDM). © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 102: 5948–5957, 2006

**Key words:** recycling; rubber; processing; ethylene–propylene–diene monomer; mechanical properties

## INTRODUCTION

When a rubber has been devulcanized, it is of interest to revulcanize it as a new product and to see whether the mechanical properties are comparable to the virgin rubber. Recycling of rubber is considered as a way to save the material cost by reshaping the used rubber into a new product or otherwise reusing it to replace some fraction of the virgin material.

The effect of incorporating reclaimed tire rubber into virgin natural rubber (NR) on the mechanical properties has been already reported.<sup>1,2</sup> The effect of the reclaimed rubber content on curing and the mechanical properties was significant. Sombatsompop and Kumnuantip,<sup>1</sup> and Sreeja and Kutty<sup>2</sup> brought up two aspects that alter these properties: the carbon black filler content (since the reclaimed rubber was mixed with the virgin one without any addition of filler) and the lower molecular weight (MW) of the reclaimed rubber. Rattanasom et al.<sup>3</sup> have studied the influence of two vulcanization systems, conventional (CV) and efficient one (EV), on the mechanical properties

of reclaimed tire rubber/NR blends at different reclaim/virgin NR ratios. Tantayanon and Juikham,<sup>4</sup> and Jacob et al.<sup>5</sup> have reported the mixing of polypropylene (PP) with reclaimed rubber to improve the mechanical properties of PP, while the incorporation of ground ethylene–propylene–diene monomer (EPDM) rubber compound into EPDM virgin rubber has been studied by Jacob et al.<sup>6–8</sup> In all the research mentioned above, the carbon black content in the compound varied with the waste rubber content, since carbon black was not added during the compounding and the waste rubber functioned as filler.

In this research, the devulcanized EPDM rubber compound was introduced into the virgin one containing the same level of carbon black filler. Hence, the carbon black contents of the revulcanizates are equal to that of the virgin rubber, and the differences in mechanical properties will be solely due to the difference in the rubber structure (crosslink density and MW) before and after it is devulcanized. Thus, the main difference compared to the earlier experiments<sup>1–6,8</sup> is that the waste rubber is treated here as a self-standing rubber compound instead of a filler.

Similar revulcanization experiments have been reported by Yun et al. using their devulcanizate (filled with up to 60 phr carbon black) from the ultrasonic grooved-barrel reactor. They reported the inferior properties of the recurred virgin/devulcanizate blend and the devulcanizate only as the result of the deactivation of carbon black due to the ultrasonic treatment.<sup>9,10</sup>

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The results of three revulcanization methods are presented here. The first part discusses the influences of accelerators and sulfur addition to the curing and mechanical properties of the revulcanizates and the possibility of blending the reclaimed rubber with the virgin material. The devulcanized EV-EPDM, which was in the first instance vulcanized using the efficient (EV) system and therefore consisted mainly of mono-sulfidic bonds, was used as the starting material.

The second part discusses the effect of various devulcanization conditions on the curing and the mechanical properties. Samples used for this part were the devulcanized SEV-EPDM, which was originally vulcanized using the semi efficient system (SEV) and therefore contained mainly polysulfidic bonds.

The third part discusses the results of using the devulcanized EV-EPDM as a replacement of the virgin SEV-EPDM material.

## EXPERIMENTAL

### Material

Hexadecylamine (HDA) from Acros was used as the devulcanization agent. Sunpar 150 oil from Sunoco B.V. was used as the plasticizer in the process. Two types of EPDM materials were examined, i.e., the efficient vulcanized EPDM (EV-EPDM) and semiefficient vulcanized (SEV-EPDM) from the production line of Hertalan B.V. The building profile EV-EPDM contains Keltan 4703, 110 phr carbon black, and an accelerator: sulfur in the ratio of 8.6 : 1; the roofing sheet contains Keltan 720, 73 phr carbon black, and an accelerator: sulfur in the ratio of 1.5 : 1. Both materials were cut into crumbs smaller than 1 cm by a rubber shredder.

### Devulcanization method<sup>11,12</sup>

The rubber crumbs were fed to the co-rotating twin screw extruder by a hopper. Processing oil (Sunpar 150) was added at the inlet. Processing oil is added to the process to lubricate the material preventing a too high processing torque. The amine (HDA) was melted at 100°C and fed as a liquid into the extruder. The rubber crumbs, oil, and amine passed through the mixing zone before entering the reaction zone. In the mixing zone, the kneading elements were mounted in a negative stagger angle to improve mixing. Negative staggered-mounted kneading section gives a negative transporting action, pushing the material backward to the feeding section until the pressure build up is high enough to overcome this. In the reaction zone, high shear rate and high devulcanization temperature (between 230 and 300°C) were applied to the mixture. Samples were taken after a steady state was reached, which could be observed from steady pressure and

temperature values. The sample was taken one residence time after the steady state was reached.

### Analysis methods

The soluble part of the devulcanized samples was analyzed in Fourier transform infrared (FTIR)<sup>13</sup> and gel permeation chromatography (GPC). The samples were extracted in acetone in a Soxhlet apparatus for 3 days to remove the low MW components. Subsequently, the rubber was dried and extracted further in toluene for another 3 days in a Soxhlet apparatus. The sol fraction in toluene was then dried in a rotavapor at 40°C and 80 mbar for GPC and FTIR analyses. FTIR was performed using Perkin-Elmer Spectrum 2000 with diamond crystal. The MW of the sol fraction is measured by dissolving the dried sample in trichlorobenzene and passing the solution through a PL Gel 5  $\mu$ m Mixed-A column at 140°C.

The rubber compound was processed on a two-roll mill to form a visually homogeneous sheet after which the activators and sulfur were added. The revulcanization conditions (temperature and time) of each sample were tested in a rubber processability analyzer (RPA2000 from Alpha Technology). The time when the torque reaches 90% of its equilibrium value ( $t_{90}$ ) was taken as the revulcanization time for each sample.

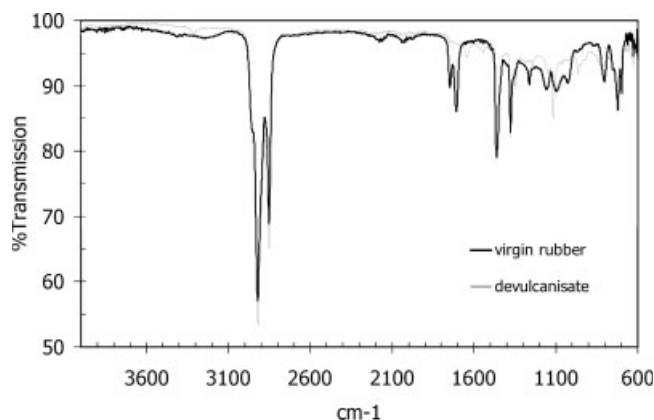
Hardness Shore A was measured for each sample. Compression set was measured at room temperature for 24 h on a specimen of 6 mm thick and 1.3 cm diameter; at least four specimens are required for each sample. Tensile-strain test was done according to ISO 37.

Crosslink density was measured by immersing in decaline for 3 days until equilibrium swelling is reached and subsequently drying the swollen sample in a vacuum oven at 80°C until constant weight was reached. Decaline was used as the swelling agent, since it gives the highest accuracy in the measurement of EPDM crosslink density among the other swelling agents (e.g., benzene, cyclohexane, etc.), due to its low solvent-polymer interaction parameter with EPDM.<sup>14</sup>

The weight of the swollen sample and the weight of the dried sample were used to calculate the relative decrease of crosslink density ([Xlink]) during the process. The apparent crosslink density was calculated using the Flory-Rehner equation as follows:<sup>1,15</sup>

$$[\text{Xlink}] = \frac{\ln(1 - V_R) + V_R + \chi V_R^2}{V_S (0.5 V_R - V_R^{1/3})}$$

where  $V_R$  is the volume fraction of rubber in the swollen sample,  $V_S$  is the molar volume of the solvent (for decaline 0.154 L/mol at room temperature), and the interaction parameter of decalin-EPDM  $\chi$  is  $0.121 + 0.278 \cdot V_R$ .<sup>16</sup>



**Figure 1** FTIR spectra of the extracted unvulcanized compound versus devulcanizates.

## RESULTS AND DISCUSSION

### EV-EPDM reclaim

EV-EPDM devulcanizates were produced in a continuous process in a co-rotating twin-screw extruder. The devulcanizates left the extruder in a strand form. A number of the devulcanized samples were analyzed by using FTIR and GPC. The results were then compared with that of the extracted fraction from the virgin compound.

Figure 1 shows the FTIR spectra of the sol fraction of the virgin EPDM. Above  $3000\text{ cm}^{-1}$  no peaks can be found in the devulcanizate, which may lead to a conclusion that there is no or very little (below the capability of FTIR to detect) amount of degradation products that contain  $\text{—OH}$  groups. Degradation of hydrocarbon polymers is believed to proceed by a free radical chain reaction, leading to the formation of  $\text{—C=O}$  and  $\text{—OH}$  groups.<sup>17</sup> Delor et al.<sup>18</sup>, Wang and Qu<sup>19</sup> have studied the thermal degradation of EPDM, which results in the formation of hydroxyl and carbonyl groups (wave number around  $3500\text{ cm}^{-1}$  and  $1700\text{ cm}^{-1}$ , respectively).

From the FTIR spectrum of the virgin rubber, absorption peaks were observed in the range of  $1740\text{ cm}^{-1}$ .

These peaks are related to the presence of  $\text{C=O}$  groups, which in this case come from the vulcanizing agents (stearic acid, ZDBC, and ZDMC) present in the compound. The weight average MW of the devulcanizate is a factor of 1.5 lower than that of the virgin material.

The soluble EPDM fraction decreases to one third of that of the unvulcanized compound. The rest of the macromolecules in the gel part were still crosslinked. The soluble fraction varies between the experiments, indicating different devulcanization levels accomplished at different devulcanization conditions.

The fact that the MW of the devulcanizate extract and the soluble fraction are lower compared to that of the virgin rubber show that the MW after devulcanization has been broadening. From this information, we might expect that the mechanical properties after curing will deviate from the original virgin rubber.

### Re vulcanization of EV-EPDM

Devulcanized EV-EPDM from a continuous experiment in a co-rotating twin screw extruder conducted at  $300^\circ\text{C}$ , 100 rpm at 3.5 kg/h rubber feed rate has been chosen for the revulcanization study due to its homogeneous appearance and highest sol fraction. This devulcanizate reached an 82% relative decrease in crosslink density, as measured by the swelling test in decaline.

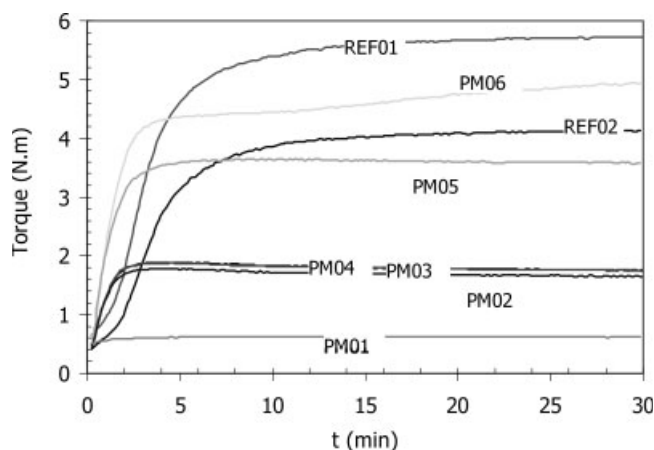
Several revulcanization recipes were applied for the EV-EPDM devulcanizate (Table I). The first experiment (PM01) was performed to check whether the accelerators were still active after devulcanization and if their addition would not be necessary. The second one (PM02) is vulcanized using an original vulcanization system that is applied to the virgin rubber compound. Experiments PM03-04 were performed to see the effect of the addition of extra sulfur and experiments and PM05-06 to check the possibility of mixing the devulcanizate into the virgin compound containing the same amount of carbon back filler (110 phr).

Experiment REF01 is a reference experiment using the virgin rubber. Since oil was added during the

**TABLE I**  
Revulcanization Scheme of the EV-EPDM

Recipe	Composition	Sulfur (phr)	Accelerator (phr)	Remarks
PM01	100% Devulcanizate	0.63	—	Recovering the 90% sulfur bonds + assuming accelerator is still there
PM02	100% Devulcanizate	0.7	6	Standard recipe
PM03	100% Devulcanizate	0.8	6	Extra 0.1 phr sulfur (14%)
PM04	100% Devulcanizate	1	6	Extra 0.3 phr sulfur (40%)
PM05	50% Devulcanizate + 50% virgin	0.7	6	
PM06	25% Devulcanizate + 75% virgin	0.7	6	
REF01	100% Virgin	0.7	6	Reference experiment, standard recipe
REF02	100% Virgin	0.7	6	Reference experiment, with an addition of 5% oil





**Figure 2** Rheometer test at 160°C to determine  $t_{90}$  for each sample.

devulcanization, the devulcanizate has a higher<sup>18</sup> oil content compared to the virgin material. Therefore, another reference experiment (REF02) was prepared with a correction of extra 5% oil. Sample REF02 was chosen as a comparison for samples PM01–PM04 since they are all composed of 100% devulcanizate.

The rheometer tests for each sample at 160°C are given in Figure 2. The graph shows that the torque only increases very slightly without any addition of accelerator (PM01), which indicates a minor revulcanization. Consequently, new addition of activators is compulsory since the old ones are deactivated. This is confirmed by the FTIR spectra in Figure 1, which shows no absorbance in the frequency range of  $1750\text{ cm}^{-1}$  for devulcanized samples.

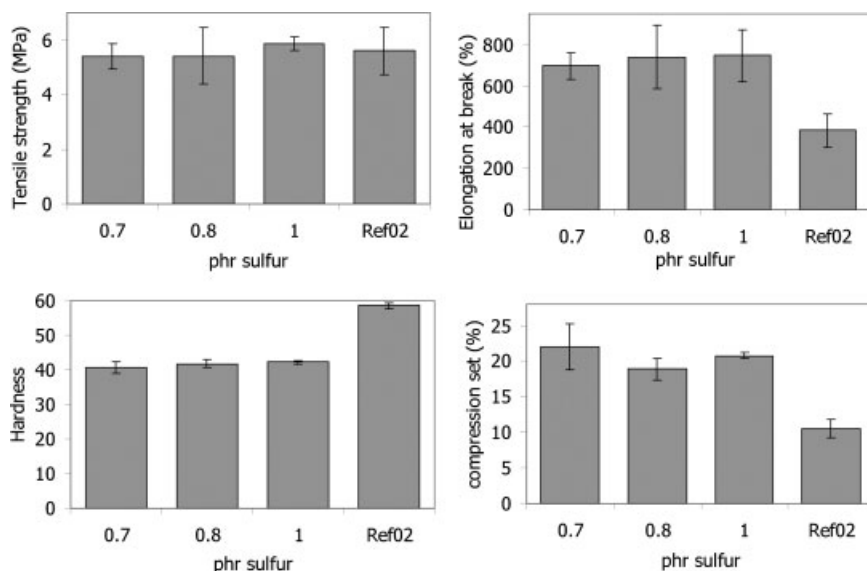
Samples PM02–04 (with 0.7, 0.8, and 1 phr sulfur respectively) exhibit similar vulcanization behavior. They only reach a final torque of 1.8 Nm and  $t_{90}$  of

96 s at 160°C vulcanization temperature, showing a little vulcanization. These results show that the addition of extra sulfur (up to 40%) does not have significant influence on the vulcanization behavior.

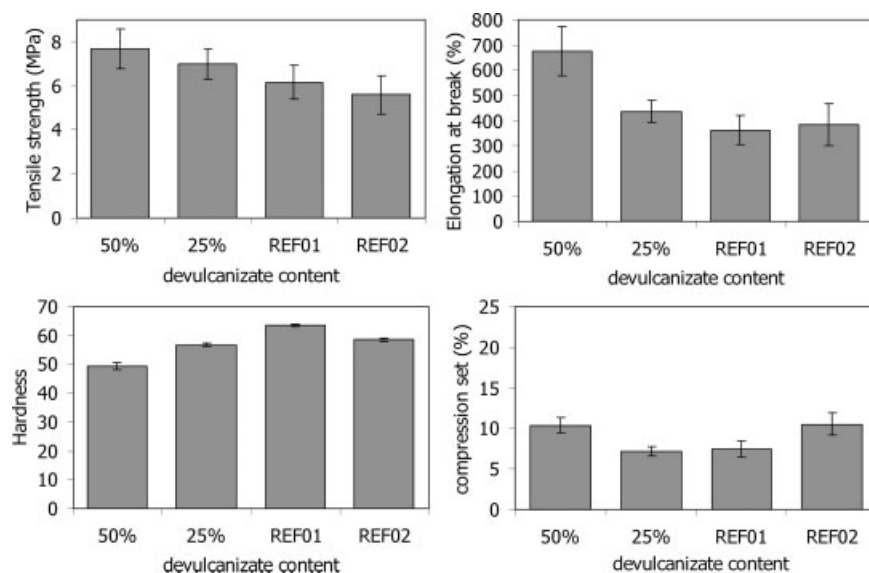
As can be seen in Figure 2, the slopes in the early minutes of all the devulcanized samples (PM02–PM06) are steeper than those of the virgin materials (REF01 and REF02), which indicates a higher curing rate of the devulcanized samples. This might be due to the still active crosslinking sites, which accelerate the crosslinking reaction.<sup>1</sup>

### Mechanical tests of the EV-EPDM revulcanizates

The graphs in Figure 3 depict the results of the mechanical tests of the samples after revulcanization at 160°C as a function of sulfur content in the recipes (samples PM02–04, compared with REF02 as the reference experiment). As can be seen, the differences in the mechanical properties between samples PM02–PM04 are not significant. The addition of sulfur up to 40% of its normal amount did not give any improvement on the mechanical properties. The tensile strength values of the devulcanizates are quite comparable with the virgin rubber, while the elongation at break values is much higher than that of the virgin rubber. The hardness drops to 40, while that of the reference experiment is 60. The compression set values of the devulcanizates are two times higher than the reference experiment. Looking at these results, we can conclude that the revulcanized rubber is softer than the virgin rubber. This corresponds to the lower crosslink density of the reclaimed rubber ( $2.4 \times 10^{-4}\text{ mol/g rubber}$ ) compared to that of the virgin rubber ( $4.4 \times 10^{-4}\text{ mol/g rubber}$ ) as measured by equilibrium swelling in decaline. A higher crosslink density leads



**Figure 3** Influence of sulfur on the mechanical properties.



**Figure 4** The influence of devulcanizate content on the mechanical properties.

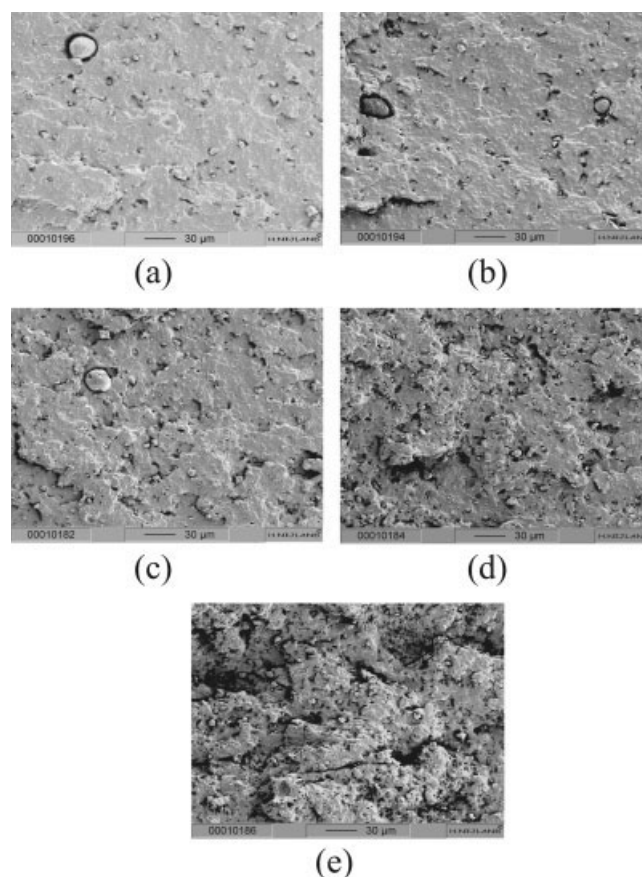
to a more limited chain mobility due to the higher permanence of the structure.<sup>20</sup> This in turn improves the elastic recovery ability of the rubber, which is represented by its compression set. Thus, the higher compression set of the revulcanizate is the consequence of its lower crosslink density compared to that of the virgin rubber. The lower hardness and the longer elongation at break of the devulcanizates are in agreement with the common tendencies with regard to its lower crosslink density compared to the virgin rubber.<sup>21</sup>

Figure 4 shows the mechanical properties of the revulcanizates as a function of devulcanized rubber content (samples PM05, PM06, REF01 and REF02). Two reference experiments are presented in the graph, since the oil content of the revulcanizates is between that of reference 1 (REF01, virgin rubber) and reference 2 (REF02, virgin rubber + 5% oil).

The mechanical properties of reference 2 are slightly inferior compared to those of reference 1. The compression set of reference 2 is 25% higher than reference 1, while the other mechanical properties are similar.

Looking at the results in Figure 4, the mechanical properties of the devulcanized/virgin rubber blends

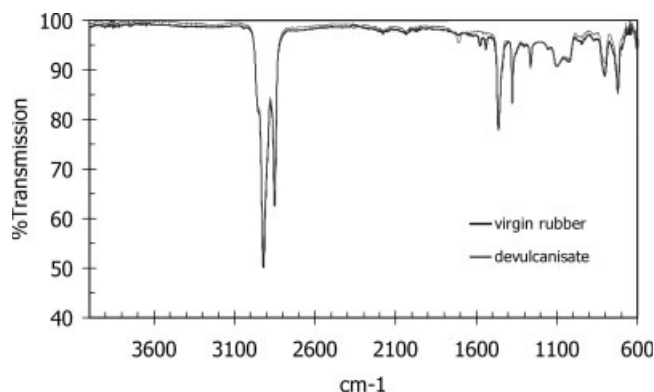
are quite comparable to those of the reference experiments. The mechanical properties of 75 : 25 blend are comparable to those of the reference experiments,



**Figure 5** SEM images of the tensile test fracture after vulcanization: (a) PM02, (b) PM04, (c) PM05, (d) PM06, (e) REF02.

**TABLE II**  
Crosslink Densities of the 50 : 50 and 75 : 25  
Revulcanizates and Reference Experiments

Sample	Crosslink density ( $10^{-4}$ ) (mol/g rubber)
Pure reclaimed	2.38
50 : 50 Virgin : reclaimed	3.29
75 : 25 Virgin : reclaimed	4.22
REF01	4.95
REF02	4.38



**Figure 6** FTIR spectra of the extracted unvulcanized compound versus devulcanizate.

while the hardness and compression set of 50 : 50 blend are slightly inferior compared to the references.

The differences in the mechanical properties might be related to the crosslink density of the revulcanizates. Table II shows the results from the equilibrium swelling measurement of the samples in decaline, showing that REF01 has the highest crosslink density, followed by REF02 and 75 : 25 (virgin:devulcanizate), and 50 : 50 (virgin : devulcanizate).

### Visualization of the products

Figure 5(a–e) are the SEM images of the fracture from the tensile test. Samples PM06 and REF02 [Fig. 5(d, e)] have irregular fibril structures. On the other hand, samples PM02, PM04, and PM05 [Fig. 5(a–c)] have a layer-like structure. This layer-like fracture might be the cause of its low tensile strength, due to stress collection on the layers where the fracture can spread easily. Because of its negative effect on the mechanical strength, this structure is thus not desired.<sup>4,6</sup>

### SEV-EPDM reclaim

The SEV-EPDM could be devulcanized at milder conditions in the extruder compared to the EV-EPDM, producing several nice samples that can easily be

processed. The experiments were conducted at 230–270°C, 3–10 kg/h, and 50–200 rpm, and 0–0.3 mol HDA/kg rubber compound. These samples were included in the revulcanization tests to study the effect of various operating conditions on the processability of the devulcanizates.

The FTIR spectra (Fig. 6) of the sol fraction of the devulcanizates are similar to the one extracted from a virgin compound, indicating that the rubber macromolecules were not significantly altered by devulcanization. Again, no peaks can be found above 3000 cm<sup>-1</sup>, which may lead to a conclusion that there are no or very little (below the capability of FTIR to detect) degradation products that contain —OH groups.<sup>17</sup>

The GPC results of samples from various devulcanization conditions showed that the devulcanizates have similar sol fractions and MWs (of the sol fractions). The sol fractions are 9–11%, or about 30% of the extractable amount of the virgin rubber, with MWs around 60% of that of the virgin rubber (96500). Again, it can be seen that the MW distribution after devulcanization is broader, and thus we might expect that the mechanical properties after curing will be inferior to the original virgin rubber.

### Revulcanization of the SEV-EPDM

Table III lists the revulcanization tests conducted on the SEV-EPDM from different extruder experiments. The samples were vulcanized using the SEV recipe, with an accelerator : sulfur in the ratio of 1.5 : 1.

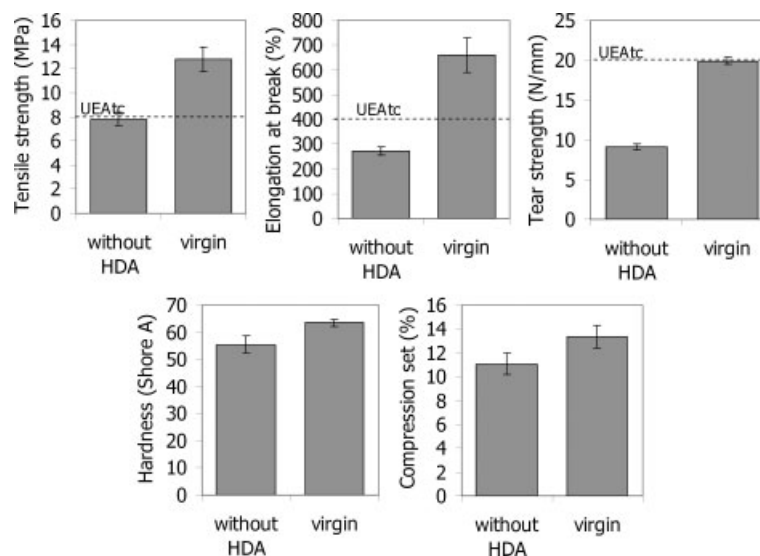
### Mechanical tests of the SEV-EPDM revulcanizates

Samples R2, R5, and R7 (Table III) were not tested further due to the presence of bulges on the surface. This surface imperfection gives a bad product appearance and disturbance during the mechanical tests, resulting in unreliable measurements.

The results of tensile-strain test, hardness, and compression set tests on the other samples are presented in Figures 7–10 as a function of devulcanization conditions, with sample REF01 (virgin compound) as the ref-

**TABLE III**  
Revulcanization Scheme of the SEV-EPDM

Sample	<i>T</i> (°C)	Flow rate (kg/h)	HDA (mol/kg rubber)	% HDA remaining (g HDA/g rubber)	Screw speed (rpm)
R1	270	3	0	100	250
R2	230	3	0.3	2.3	100
R3	230	10	0.1	0.1	100
R4	270	3	0.1	0.2	100
R5	270	3	0.3	2.4	250
R6	270	10	0.1	0.0	250
R7	270	10	0.3	3.3	100
R8			Virgin compound		
R9	270	10	0.1	0.1	100



**Figure 7** Mechanical properties of sample R0 (devulcanized without HDA) compared to those of virgin rubber (REF).

erence. The dashed lines in these figures are showing the standard UEAtc standard values<sup>22</sup> (the European standard for roofing sheet application).

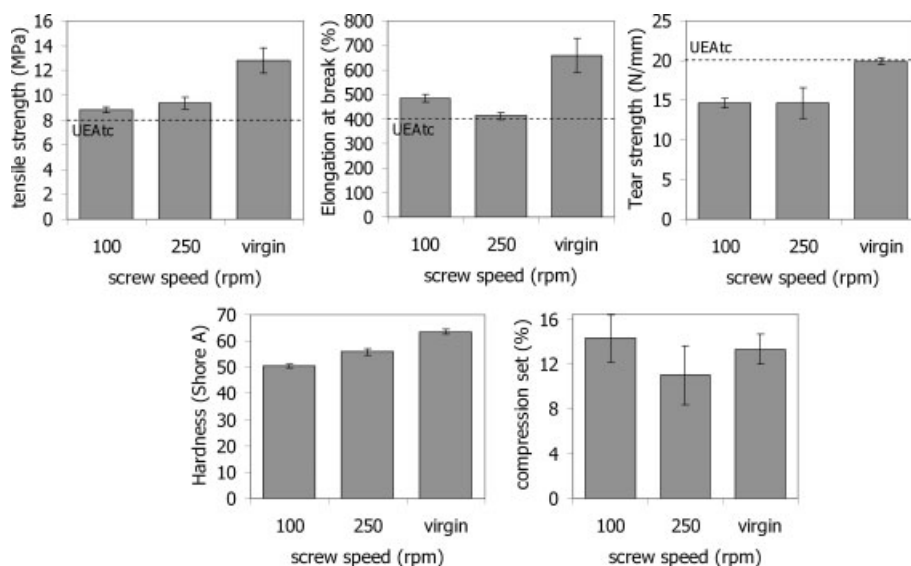
Figure 7 presents the tensile strength and hardness test of sample R0, which was devulcanized without any HDA. It performed surprisingly well in the mechanical tests except in the tensile strength and elongation at break, which is most probably caused by the inhomogeneity due to the presence of the aggregates at a very low devulcanization degree.

In Figure 8, the mechanical properties are plotted as a function of devulcanization screw speed ( $\sim$ shear rate). The differences between samples R9 (100 rpm) and R6 (250 rpm) are not significant; they both show

inferior properties compared to the virgin rubber, except in the compression set, which is approximately the same as the reference experiment.

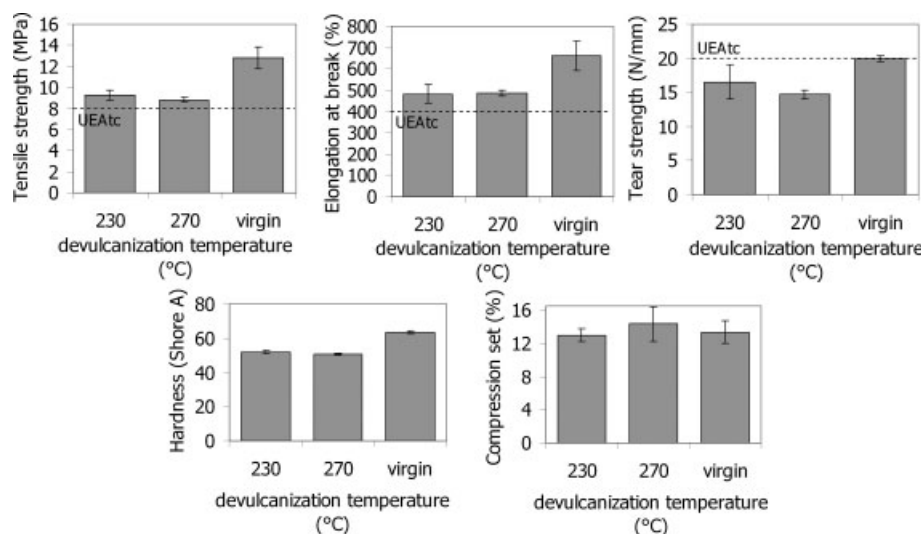
The mechanical properties are plotted as a function of devulcanization temperature in Figure 9. The same tendency is observed again: the differences between the two samples are not significant, and both have inferior properties compared to the virgin rubber except their compression sets.

Figure 10 plots the mechanical properties as a function of devulcanization flow rate (which is more or less inversely proportional to the residence time). According to the hardness and tensile-strain tests, the sample produced at lower flow rate (3 kg/h) is



**Figure 8** Influence of devulcanization screw speed on the mechanical properties (10 kg/h, 0.1 mol HDA/kg rubber, 270°C).





**Figure 9** The effect of devulcanization temperature on the mechanical properties (10 kg/h, 100 rpm, 0.1 mol HDA/kg rubber).

somewhat softer than that at higher flow rate (10 kg/h), while their compression sets are similar. This might be caused by the further network breakage or further degradation at longer residence time, which adversely influences the mechanical properties after revulcanization.

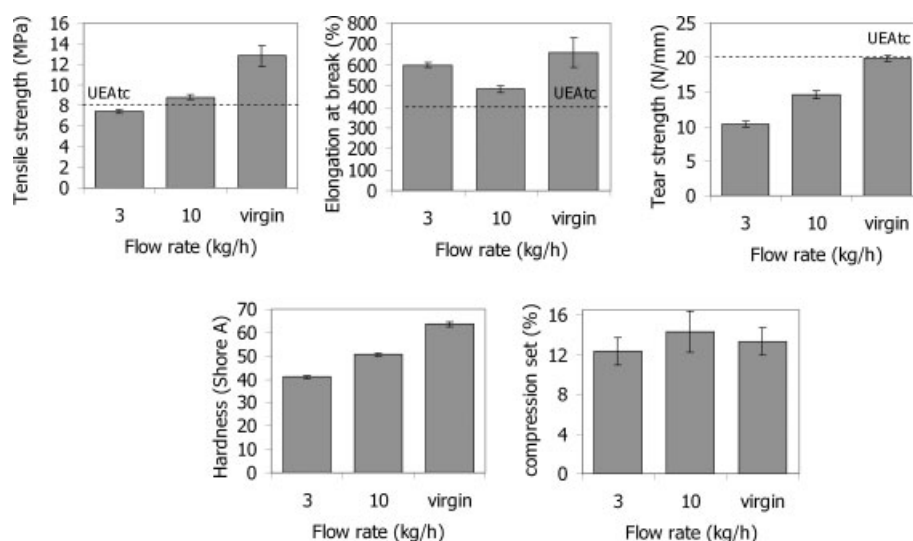
From all the results above, it can be concluded that the tensile strength seems to be the toughest property to fulfil for the reclaimed SEV-EPDM samples, while the compression set is the easiest one to retain.

In spite of the excessive amount of devulcanizing agent in the reclaimed rubber, the effect of the devulcanization conditions can hardly be observed in the revulcanizate properties. On the other hand, devulcanization without using any chemical results in a

crumb-like devulcanizate, which in turn contributes to a very poor tensile strength. Hence, a devulcanization agent is necessary but the amount added should not be too much to avoid surface imperfection.

### Visualization

Surface imperfection was observed on samples prepared in the extruder with a concentration of HDA higher than 0.15 mol/kg rubber. This might be due to interaction between gaseous components present in the devulcanizate and the properties of the devulcanizate (for example its surface tension, elasticity, and early curing because of the still active crosslinking sites) so that some gas is trapped in the rubber. Since



**Figure 10** The effect of devulcanization flow rate on the mechanical properties (270°C, 100 rpm, 0.1 mol HDA/g rubber).



**Figure 11** A surface photo of a revulcanized sample with bulges.

the vulcanization in the press was conducted at 100 bar, it is suspected that the bulges were already formed during the degassing (bumping) step prior to the pressing.

The gaseous component involved in the bulge forming is most likely HDA, with a boiling point of 330°C and flash point of 140°C, which might be leaving the rubber at the vulcanization temperature, forming bulges (up to 4 mm in diameter), as shown in Figure 11. This is supported by the FTIR spectrum on the deposit of the vapor trapped during the heating of the devulcanizate at 140°C (vulcanization temperature), which is similar to that of the HDA. A thermogravimetric analysis (TGA) done on the devulcanizate at 140°C showed a 3.2% weight loss fraction after 60 min of heating. This amount is equal to the amount of HDA

remaining in that sample according to HDA analysis in GC on the hexane extract of the devulcanizate.

Despite the fact that using higher concentration of HDA in the devulcanization process leads to a higher conversion, this causes surface imperfection of the revulcanizate. Hence, the amount of HDA used in the devulcanization process should be optimized to give enough conversion and as little as possible HDA remaining in the rubber.

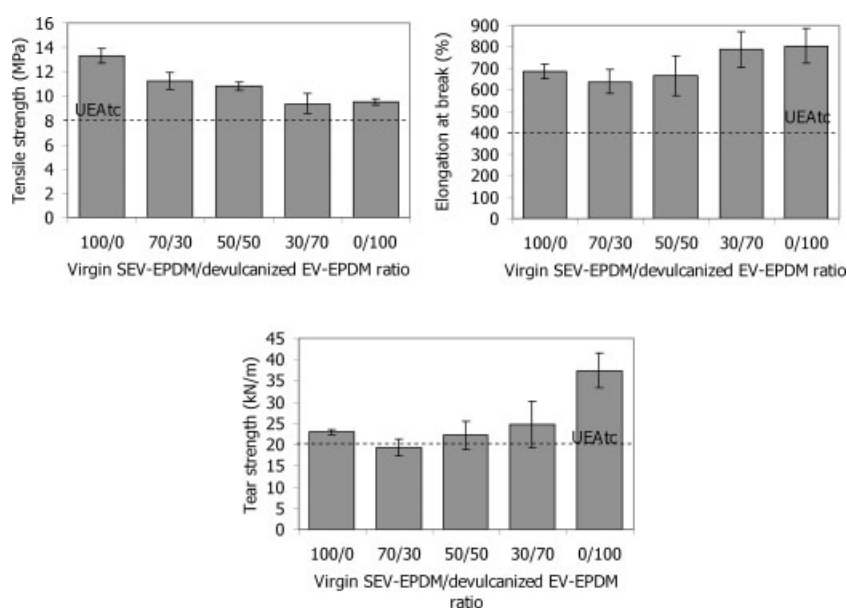
### Blending of EV-EPDM devulcanizate into the virgin SEV-EPDM compound

Another revulcanization method has also been tested, using the devulcanized EV-EPDM produced in the continuous devulcanization process developed here. The devulcanizate was blended into the virgin SEV-EPDM and curing was performed by using the vulcanization system of the latter at the corresponding vulcanization temperature, where no marching modulus and no reversion were observed.

The results of the tensile strength, elongation at break, and tear strength tests are depicted in Figures 12(a–c), respectively. The tests give excellent results, where almost all the properties are still above the UEAtc standard,<sup>22</sup> except the tear strength of the 70/30 compound [Fig. 12(c)].

The tensile strength and elongation at break are above the standard even for the 100% devulcanized EV-EPDM. Surprisingly, its tear strength is even higher than the virgin roofing sheet.

Looking at these results, it seems that the use of the devulcanized EV-EPDM to replace the virgin SEV-EPDM for roofing sheet application is a viable option.



**Figure 12** Results of the (a) tensile strength tests, (b) elongation at break, (c) tear strength for several virgin SEV-EPDM/devulcanized EV-EPDM after revulcanization.

## CONCLUSIONS

The devulcanized rubber produced in this research can be revulcanized to obtain a new rubber product using the same recipe of the corresponding virgin rubber. The mechanical properties of the revulcanizate without any addition of virgin material are inferior in comparison with those of the virgin rubber, which is not surprising considering the broader MW distribution and lower average MW of devulcanizate extract (as measured by sol–gel test and GC). The revulcanized blends of devulcanizate with virgin material have shown that at least 25% of the devulcanizate can be added to the virgin material without deteriorating the mechanical properties.

In case of EV-EPDM revulcanizates, the hardness and compression set are the difficult mechanical properties to sustain, while the tensile strength and elongation at break are the tough ones in case of EPDM roofing sheet revulcanizates. Thus, the challenging mechanical properties to keep up differ for different types of EPDM rubbers.

Blending a devulcanizate into another type of EPDM rubber compound or reusing it in different application is a good option, as has been shown here. Curing EV-EPDM devulcanizate using the vulcanization system for roofing sheet produced material that complies with its application standards even at 100% devulcanizate content.

## NOMENCLATURE

EV-EPDM	Efficient-vulcanized EPDM
HDA	Hexadecylamine
NR	Natural rubber
SEV-EPDM	Semi efficient-vulcanized EPDM
$V_R$	Volume fraction of rubber in swollen gel
$V_S$	Molar volume of the solvent (L/mol)
[Xlink]	Crosslink density (mol/g rubber)

$\chi$

Interaction parameter between EPDM rubber and decaline

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